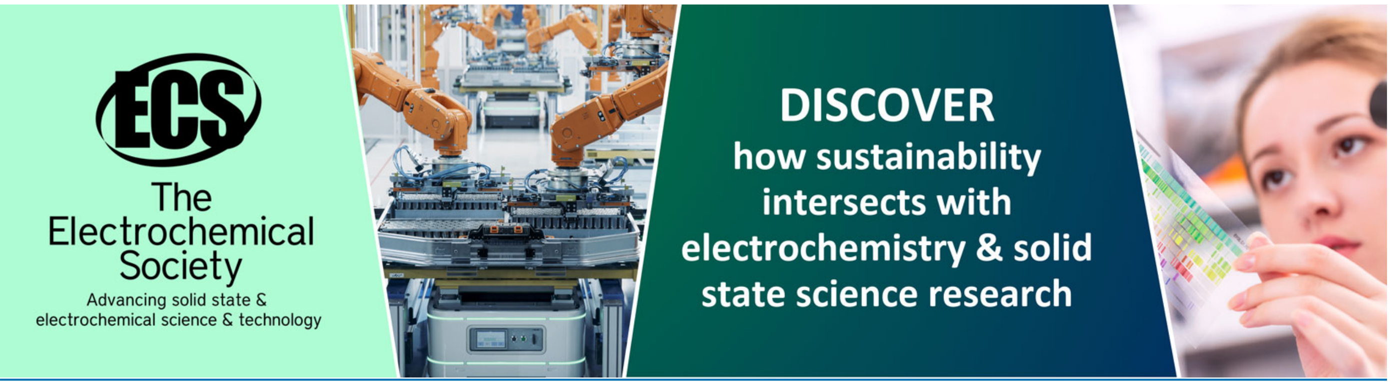
IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Numerical simulation on rectifying flow in intake system of a pumping station connected with headrace pipe

To cite this article: D Zi *et al* 2016 *IOP Conf. Ser.: Earth Environ. Sci.* **49** 032004



Numerical simulation on rectifying flow in intake system of a pumping station connected with headrace pipe

D Zi[1], F J Wang[1], Z F Yao[1], R F Xiao [1], X Chen [1] and C L He[2]

[1] College of Water Resources and Civil Engineering, China Agricultural University, Beijing, 100083, China
[2] China Water Resources Beifang Investigation Design and Research Co. Ltd, Tianjin, 300222, China

evangeline_13@126.com, wangfj@cau.edu.cn

Abstract. Pipes are usually adopted in those conditions for which the pump house is far from water source. As for fore-bay, flow of headrace pipe can be considered as jet-flow. Jet-flow has a high velocity, and creates large pressure gradient between jet-flow and near wall flow, which contributes to large scale circulation. In that circumstance, a single rectification measure cannot effectively improve the flow pattern of intake flow field. For large scale pumping station, there is enough space to arrange complex anti-vortex devices. Thus, a new type of combined diversion piers composed of double-I type pier, three-I type pier and cross anti-vortex baffle was proposed. In order to investigate the influences of combined division piers on flow pattern, four cases with different geometry and location parameters are designed. The results of numerical simulation and site tests show that the combined diversion piers could effectively improve the intake flow field of pumping station with headrace pipe. As for pumping station with headrace pipe, the distance between inlet section of fore-bay and leading edge of double-I type diversion pier should be $0.25L$-$0.53L$ (where L is the length of fore-bay). The distance between inlet section of fore-bay and trailing edge of double-I type diversion pier should be $0.5L$-$0.73L$. The total length of double-I type pier should be $0.2L$-$0.25L$.

1. Introduction

The aim of fore-bay and sump is to provide water with uniform velocity for a pumping station. The abnormal flow phenomena such as cavitation, flow separation, vibration and noise occur often due to unreasonable design of fore-bay and sump. Large scale circulations, free and subsurface vortices containing air occurred in intake field seriously damage pumping station. Therefore, many researchers have studied corresponding facilities to improve the flow pattern of intake flow.

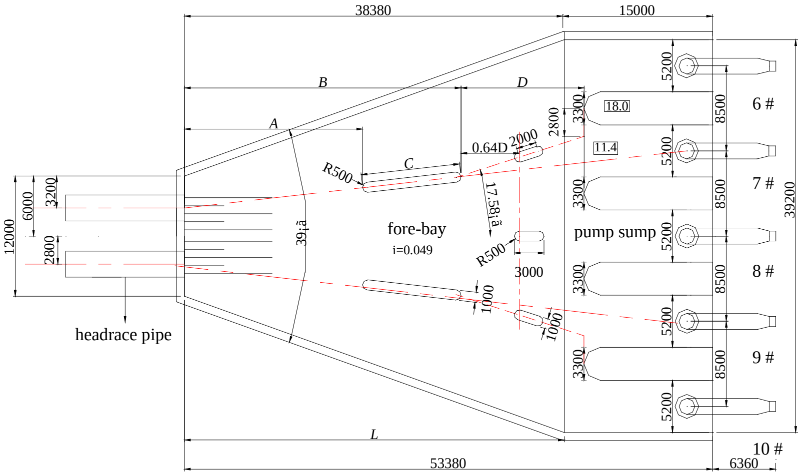
The anti-vortex devices can be divided into: division piers, bottom sills, columns, curtain wall, anti-vortex baffle and so on [1]. Chen adopted Y-shaped division pier to improve the flow pattern in the front inflow field [2]. Lu studied the details of flow pattern after setting a double-I type pier [3]. Tanweer compared the differences of hydraulic performance of fore-bay and sump between the original design and optimized design with guide vanes [4]. Kim used fillets and splitter to eliminate submerged vortex around bell-mouth [5]. Kang studied the effect of different types of anti-vortex device on suppressing the vortices, and he believed that the splitter with trapezoidal section is the most effective one [6]. Those different prevention vortex devices applied to different pumping station have produced positive effects.

The flow pattern formed in intake field for a pumping station with headrace pipe is different from the one with open channel. As for fore-bay, flow of headrace pipe can be considered as jet-flow. Circulation caused by jet-flow is much stronger than that caused by diffusion flow. Circulation caused by jet-flow has great influence of flow under bell-mouth, and it may bring air into pump. Therefore, rectification measures are needed to optimize the flow field of pumping station with headrace pipe. Some time, a single rectification measure cannot effectively improve flow pattern of pumping station with headrace pipe. Some people illustrated that combined anti-vortex devices could achieve a better performance [7-8]. But there is little research about layout plan of combined devices and analyses on rectifying effects. So the Yonghu pumping station, a pumping station with leading pipe, which is located in Guangdong province, was taken as a research object. This paper studies the effects of combined division piers on flow rectification, analyzes the influences of the location and geometry parameters on hydraulic performance, and finally gives the recommended values of corresponding parameters.

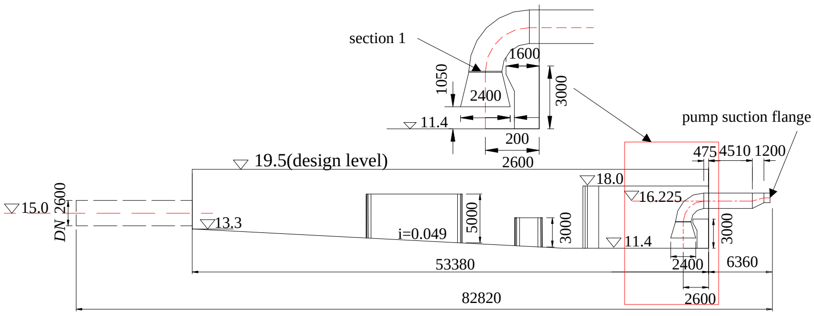
2. Geometry and problems

2.1. Fore-bay and sump geometry

Yonghu Pumping Station installed five double suction centrifugal pumps (four pumps for work, and one for standby). The pumping station has two leading pipes carrying 15m^3/s (total flow), and the diameter of the headrace pipes is 2.6m. The bottom slope coefficient of fore-bay is 0.049, and the fore-bay is 38.38m long with an overall expansion angle of 39°ending in a rectangular sump of 15m×39.2m. The sump has five bays separated by piers of length 13m and width 3.3m. The inner diameter of bell-mouth is 2.4m, the clearance of back wall is 0.2m, and the clearance from sump bottom is 1.05m (see Figure 1).



(a) Plan view



(b) Elevation view

Figure 1. Schematic structure of Yonghu pumping station

2.2. Flow problems

The pumping station was built in 2008. During its operation, there were evident vibration and noise. The main problems could be generalized into: (1) many large scale circulations and surface vortices (see Figure 2); (2) violent vibration of the water pump unit. The vibration velocity RMS (Root Mean Square) values of driving end and non-driving end bearing housing are 5.10mm/s and 5.96mm/s respectively, highly greater than 2.8mm/s, which is the vibration level D specified in the national standard [9], and in that level pumps cannot normally work; (3) large pressure fluctuation of pump, because the floor of pump house had a resonance phenomenon [10].

(a) Fore-bay (b) Pump sump

Figure 2. Circulations and surface vortices inside fore-bay and pump sump

The bad flow condition is the important factor resulting with low efficiency and vibration. Through the analyses of the geometry of fore-bay and pump sump (see Figure 1), the reasons which caused high pump vibrations and noise could be summarized as the following aspects: (1) large expansion angle, nearly close to the maximum value of the standard; (2) jet-flow, caused by high speed current from leading pipe; (3) low height of piers; (4) inappropriate clearance of back wall and clearance from sump bottom; (5) no anti-vortex device under the bell-mouth.

3. Mathematical model

3.1. Governing equations and turbulence model

In this research, the flow in the fore-bay and sump is treated as turbulent incompressible flow. The governing equations for this problem are the steady-state RANS equations for the conservation of mass and momentum [11]. The RNG $k-\varepsilon$ model is adopted to simulate the effect of turbulence [12].

3.2. Boundary conditions

Figure 3 shows the solution domain for the numerical simulation. The inlet condition is specified as mass flow inlet. The outlet section corresponds to the actual location of pump suction flange and is set to outflow condition. The free surface of fluid is specified as a symmetry boundary i.e. a stress free plane of symmetry or surface across which no flow takes place. No slip boundary conditions and standard wall functions are used for the solid walls. The control finite volume method is used to simulate the computational domain. The pressure-velocity coupling scheme is SIMPLEC. The second-order upwind difference scheme is used for the momentum, turbulence kinetic energy and turbulence dissipation rate equations.

3.3. Computational grid

Because of the complex topology of sump, the domain was meshed with an unstructured mesh of tetrahedral cells (see Figure 3). The global element seed size of grid was 0.4m, and the local refined size was 0.2m (exclude the grid of cross anti-vortex baffles with 0.05m). A grid sensitivity study was carried out to assess the required mesh density. Several grids were calculated, ranging from 0.86

million up to 4.98 million. No further convergence was obtained for grids with more than 2.05 million cells. The numerical analyses were carried out in FLUENT, and flow was analyzed with the help of TECPLOT software. It took nearly 7 hours for one simulation in a computer with CPU E5-2630.

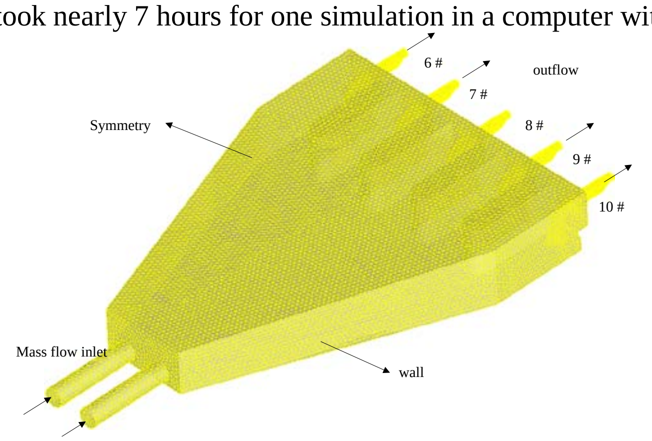


Figure 3. Computational domain and boundary conditions

3.4. Calculation case

There are four types of improved cases to decrease vortices. The width of piers in the fore-bay is 1m. The height of the double-I type diversion pier and the three-I type division pier is 5m and 3m respectively. The design variables of the combined diversion piers are *A*、*B*、*C*、*D* (see Figure 1). Location parameter *A* indicates the distance between inlet section of fore-bay and leading edge of double-I type diversion pier. Location parameter *B* indicates the distance between inlet section of fore-bay and trailing edge of double-I type diversion pier, and geometry parameter *C* indicates the length of double-I type diversion pier. Location parameter *D* indicates the distance between trailing edge of double-I type diversion pier and inlet of sump pier.

The distance between the double-I type diversion pier and the three-I type division pier should be appropriate. There are little effects on flow pattern in sump if the three-I type division pier is close to the double-I type diversion pier. While it worsen the flow pattern in sump if the three-I type division pier is moved apart from the double-I type diversion pier. In other words, it's harmful to the flow pattern in the sump if the three-I type division pier is close to bell-mouth. Through those analyses, it is found that a good result can be obtained when the distance is equal to 0.64*D*, and *D* is a location parameter, as defined in Figure 1.

Calculation cases are showed in Table 1.

Table 1. Calculation cases for CFD simulation

Case	*A* (m)	*B* (m)	*C* (m)	cross anti-vortex baffles
[a]0	0	0	0	no
1	10	19	9	no
2	18.5	27.5	10	no
3	23	29	6	no
[b]4		——		yes

[a] Case 0 is the original design without improved facilities.
[b] Case 4 is a combination of the best one from case 1 to case 3 and cross anti-vortex baffles.

4. Simulation results and discussions

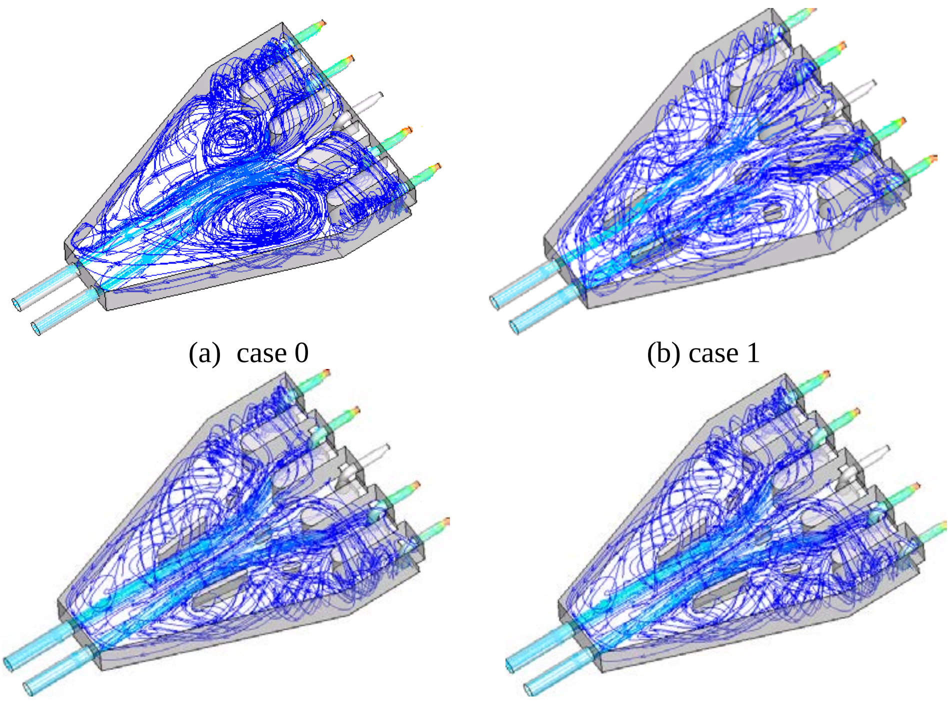
4.1. Flow patterns of division piers

Table 2 shows the hydraulic head losses for four cases. h_1 presents the hydraulic head loss from the inlet of the computational domain to the bell-mouth, h_2 presents the hydraulic head loss from bell mouth to the outlet of the domain, h presents the total hydraulic head loss of the domain. From Table 2 it can be shown that the head losses of improved cases are smaller than that of case 0. In order to get a further understanding, comparisons of flow patterns are taken to get the advantages and disadvantages of each case.

Figure 4 shows the flow patterns for the four cases. It can be shown that the flow pattern of the case 0 (original design without any pier in the fore-bay) is poor. There are two large recirculation zones in the fore-bay and pump sump. Near the back wall zones of sump, cross flow is also generated. Furthermore, spiral vortices exist in the two sides of the sump. Compared to the site test (shown in Figure 1), the results of simulation are consistent to the experiment.

Table 2. Hydraulic head losses of the four cases (m)

Case	h_1	h_2	h
0	0.181	0.070	0.250
1	0.167	0.043	0.210
2	0.166	0.063	0.229
3	0.172	0.051	0.224



(a) case 0 (b) case 1

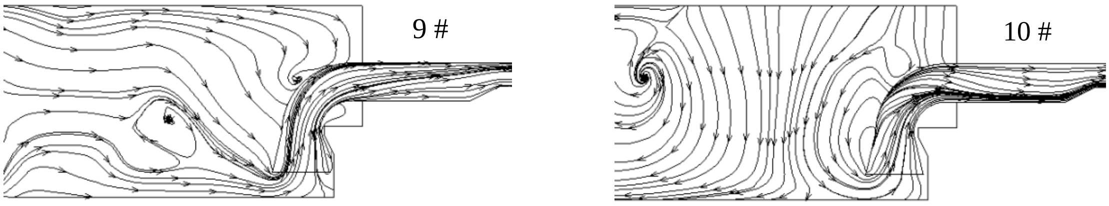
(c) case 2 (d) case 3

Figure 4. Global flow patterns for four cases

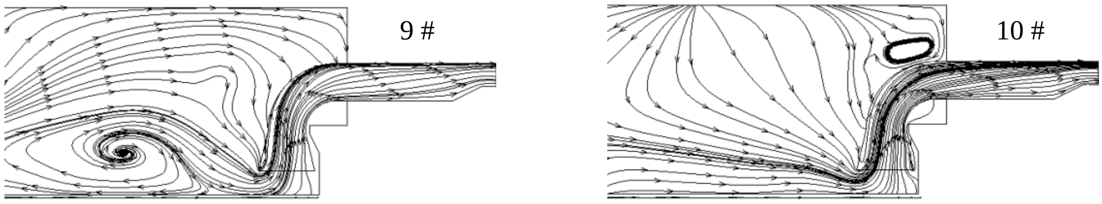
If there is no pier in the fore-bay, the flow pattern of intake flow field is much worse. As the double-I type pier and the three-I type pier are installed in the fore-bay, the large circulations are disappeared. All of the three cases with division piers improve the flow pattern of flow field.

Figure 5 shows velocity streamlines in the vertical axial section of sump and suction pipe. Because of the symmetry, just one half of the intake pump is analyzed in this study. Therefore, two pumps, as shown in figure 5, will be concerned in the follow (pump 9# and pump 10# are taken as the analysis objects in this paper). From the figure it can be seen that there are deformations of streamlines in suction pipes of case 0. Especially, the streamlines of pump 10# have been distorted into “S” type, which will affect the safe operation of pumping station.

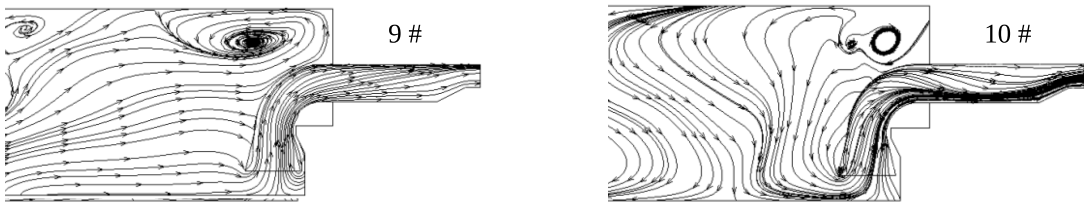
However, the streamlines in suction pipe are gradually smooth when the double-I type pier and the three-I type pier are installed in the fore-bay. Compared with the three optimized cases, it can be seen that both case 1 and case 2 have improved the flow pattern of intake field, but case 3 is not as good as the two previous cases.



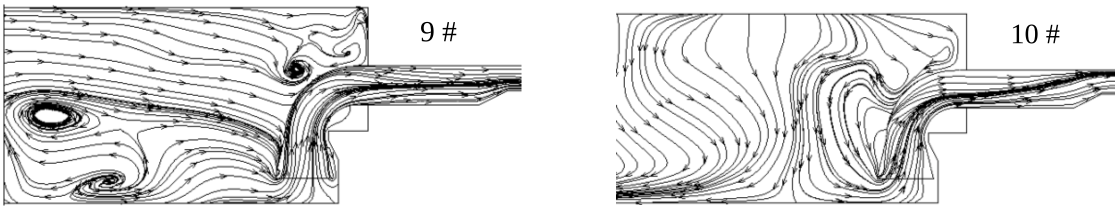
(a) case 0



(b) case 1



(c) case 2



(d) case3

Figure 5. Velocity streamlines in the vertical axial section of the four cases

The uniformity of axial velocity distribution at the bell-mouth can be used as a quantitative evaluation standard for the flow pattern of intake flow field. Therefore, the uniformity of axial velocity distribution and the axial velocity angle are given by [13]:

$$V_u = [1 - \frac{1}{\overline{u_a}}\sqrt{\frac{\sum (u_{ai} - \overline{u_a})^2}{m}}] \times 100\% \tag{1}$$

$$\overline{\theta} = \sum u_{ai}(90^\circ - arctg\frac{u_{ti}}{u_{ai}}) / \sum u_{ai} \tag{2}$$

Here, V_u is the uniformity index of velocity distribution, $\overline{\theta}$ is the average axial velocity angle, m is the number of cell i, $\overline{u_a}$ is the average axial velocity, u_{ai} is the axial velocity of cell i, u_{ti} is the transverse velocity of cell i.

In order to avoid the error caused by mesh interface, section 1 (its diameter is 1.6m) is taken as an evaluation standard of bell-mouth (see Figure 1b). Thus, the average axial velocity of bell-mouth section calculated by hydraulic formula is 1.865m/s. It can be seen from the Table 3 that the value calculated by one dimensional hydraulic formula is quite similar to that of the numerical value obtained by simulation.

As can be seen in the Table 3, both case 1 and case 2 improve the uniformity index of velocity distribution. But for case 3, compared to the case 0 with no improved measures, its uniformity index of velocity distribution is decreased. That is to say, the arrangement of piers like case 3 does no effect on rectifying flow pattern of intake field, but worsen it.

Table 3. Uniformity index of velocity distribution of bell-mouth section of the four cases

Case	$\overline{u_a}$ (m/s)	V_u (%)	$\overline{\theta}$(°)
0	1.893	77.649	80.238
1	1.864	79.270	82.171
2	1.859	78.573	79.086
3	1.854	76.221	79.217

Taking Figure 4, Figure 5 and Table 3 into consideration, case 2 is the best one of the three cases with double-I type pier and three-I type pier. Looking at case 1 there is a vortex in front of bell-mouth of pump 9#, which is harmful to the hydraulic performance of pump. The streamlines in the suction pipe of pump 10# of case 2 is not good as case 1. Although in some aspects, the flow pattern of case 2 is slightly worse than that of case 1, it can be improved by adding anti-vortex device below the bell-mouth. So based on case 2, a research on cross anti-vortex baffles for improving flow pattern is taken.

4.2. Flow pattern of cross anti-vortex baffles

Figure 6 shows schematic of cross anti-vortex baffles. According to Table 1, the case combining case 2 and cross anti-vortex baffles can be named as case 4.

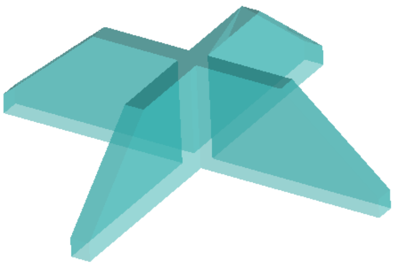


Figure 6. Schematic of cross anti-vortex baffles

Figure 7 shows the velocity streamlines in the vertical axial section of case 4. It can be seen that the flow pattern of case 4 is much better than that of the previous four cases. For case 4, the streamlines in the suction pipe of pump 9# and pump 10# are much smoother than that of every previous case. Streamlines in suction pipes have no distortion and provide completely smooth flow to the inlet of the pump.

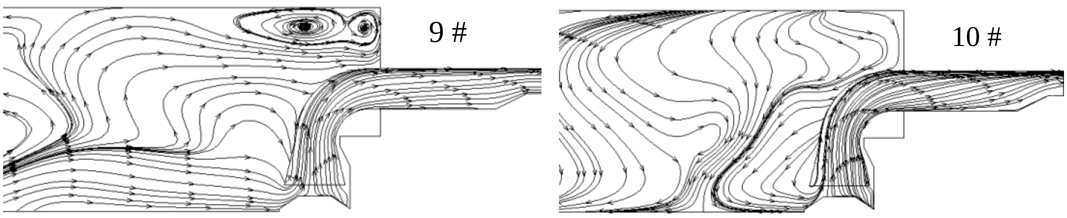


Figure 7. Velocity streamlines of the vertical axial section of case 4

The average axial velocity of bell-mouth section of case 4 obtained by simulation is 1.874m/s. The uniformity index of axial velocity distribution is 83.935%, and the average axial velocity angle approaches 82.188° .Compared to case 0, the uniformity index of velocity distribution and axial velocity angle of bell-mouth section raise 6.286% and 1.95° respectively.

Figure 8 shows the vorticity magnitude of the floor attached vortex in sump. It is clear that the magnitude of floor attached vortex for case 4 is significantly lower than that of case 0. The solid circle vortex cores are broken up by cross anti-vortex. That means the cross anti-vortex baffles have produced a positive influence on flow pattern in intake flow field.

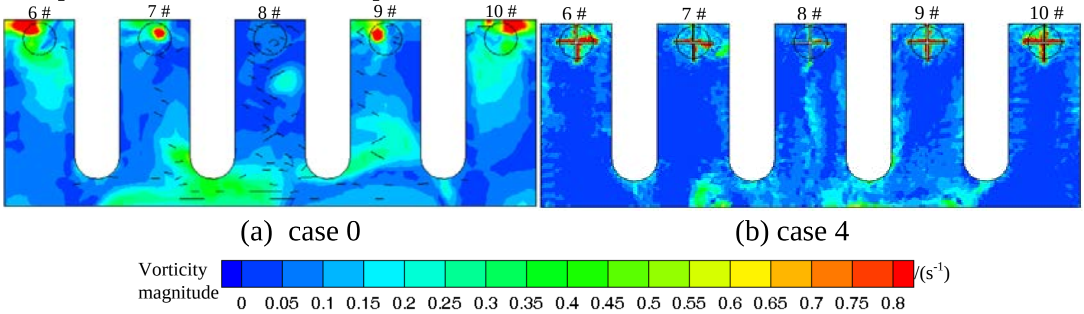


Figure 8. Vorticity magnitude of floor attached vortex in sump at case 0 and case 4

4.3. Analyses of site tests

According to the above analyses, it is known that case 4 can effectively improve the flow pattern of fore-bay and sump. Figure 9 shows the real structure of the combined division piers of Yonghu pumping station.

(a) Front view (b) Side view

Figure 9. Photograph of the fore-bay and pump sump of case 4

The second site test was carried out during the operation of pumping station. Table 4 shows the pressure fluctuation of pump 6# in the two site tests, and Table 5 shows the vibration velocity RMS of pump 6# in the two site tests [10].

Table 4. Peak-to-peak value of pressure fluctuation of pump 6# (m)

Case	Outlet of pump	Top of pump casing
0	4.59	8.07
4	2.72	6.69

Table 5. Vibration velocity RMS values of pump 6 # ($mm\cdot s^{-1}$)

Case	Driving end bearing housing			Non-drive end bearing housing		
	Vertical	Radial	Axial	Vertical	Radial	Axial
0	2.40	5.10	2.35	3.12	5.96	2.73
4	1.84	2.13	2.80	1.38	2.05	2.47

As it is shown in Table 4, the peak-to -peak value of pressure fluctuation of outlet of pump and top of pump casing of case 4 is quite lower than that of case 0. The maximum value of peak-to-peak value of pressure fluctuation falls from 8.07m to 6.69 m, decreased by 17.1%. As can be seen in Table 5, the vibration velocity RMS of driving end and non-driving end bearing housing are greater than 2.8 mm/s, namely the vibration level D [9]. But as for the case 4, the vibration velocity RMS values of pumps are less than or equal to 2.8mm/s, in other words, the vibration level is C [9], and the pumping station could operate normally. The numerical simulation and site tests performed show that the type of combined division piers could effectively improve the intake flow field of pumping station.

4.4. Analyses of combined diversion piers' geometry

By the numerical simulation and site tests, it is obvious that the combined division piers have many positive effects in improving intake flow pattern of pumping station with headrace pipe. From Table 3 we can see that the combined division piers have little impact on the average axial velocity angle, but they have a significant effect on the uniformity of axial velocity distribution. So, the uniformity of the axial velocity distribution at the bell-mouth section 1 is taken as a target variable. The relationships between target variable and parameters of piers are analyzed, as shown in Figure 10, where parameters *A*, *B*, *C* are referred to *L*, namely the length of fore-bay.

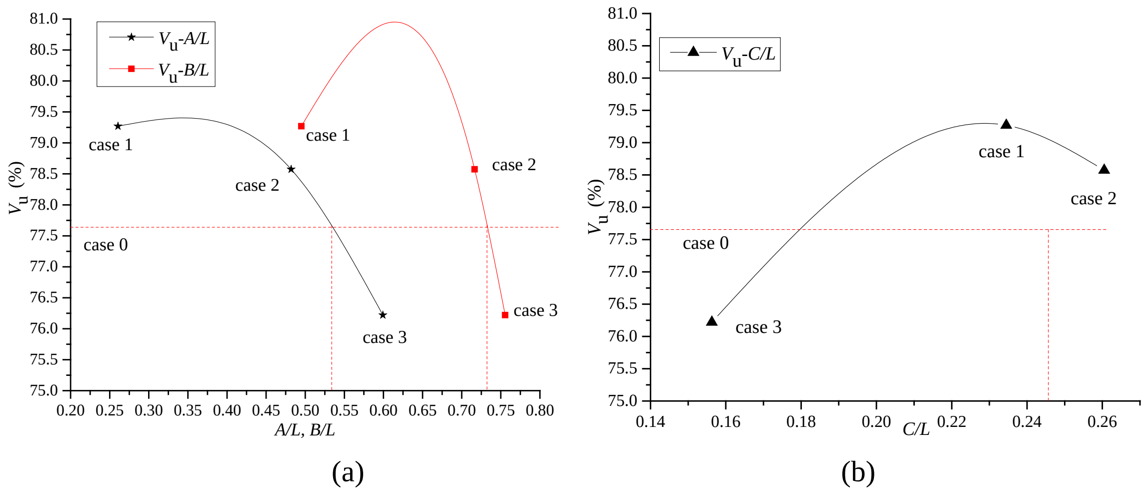


Figure 10. Uniformity of axial velocity distribution of different parameters of double-I type pier

As it can be seen in the Figure 10, the uniformity of axial velocity distribution is greater than 77.649% (the uniformity of axial velocity distribution of case 0) if *A*/*L* of the combined division piers ranges from 0.25to 0.53, and it reaches the maximum value when *A*/*L* is equal to 1/3. The combined division piers can improve the flow pattern if *B*/*L* of the combined division piers is in the range 0.5 to 0.73, and achieves the best effects when *B*/*L* is 0.61. The flow pattern is improved when *C*/*L* of the combined division piers lies between 0.18 and 0.25, and gets its best performance when *C*/*L* is equal to 0.23. However, structure parameter cannot be separated from the location parameters, so the value range of *C*/*L* can be narrowed down to 0.2-0.25.

5. Conclusion

Based on the three dimensional numerical simulation and site tests, this paper studies the effects of combined division piers on rectifying intake flow field for a pumping station with headrace pipe. The location and structure parameters are also analyzed. The numerical results show that the combined division piers could eliminate the large circulations and vortices caused by jet-flow. The jet-flow is caused by high speed flow from the headrace pipe.

As for the combined division piers, the front double-I type diversion pier reduces expansion angle of the fore-bay, and decreases the size and strength of surface vortex. The three-I type pier adjusts the uniformity of flow field, and water flow is well introduced to the corresponding pump sump. Floor attached vortices are almost completely eliminated by the cross anti-vortex baffle. Flow pattern is uniform and smooth in the inlet of pumps.

The location of the front double-I type diversion pier and three-I type pier has a great effect on the flow pattern. Their location can't be too close or too far away from the fore-bay or the flow pattern in the fore-bay and sump will be worse. The flow pattern in intake flow field will be better when the length of the double-I type diversion pier is no more than 0.25*L*, and no less than 0.2*L*. The distance between inlet section of fore-bay and leading edge of double-I type diversion pier should be about 0.25*L*-0.53*L*. The distance between inlet section of fore-bay and trailing edge of double-I type diversion pier should be about 0.5*L*-0.73*L*. The recommended value of distance between the double-I type diversion pier and the three-I type division pier should be 0.64*D*.

Acknowledgements
This work is supported by the National Key Technology R&D Program of China (No. 2012BAD08B03) and the National Natural Science Foundation of China (No. 51321001).

References
[1] Wang F J 2005 *Pump and Pumping Station* (Beijing: China Agriculture Press)
[2] Chen L, Qi W J, Luo C, Shang Y N and Yuan H Y 2014 Effect of geometric parameters of Y-shaped diversion piers on flow pattern in forebay of pumping station *Advances in Science and Technology of Water Resources* **34**(1) 68-72
[3] Lu X R, Tong H W and Feng J G 2007 Measures of improving flow patterns for entrance bays of city intake water pumping stations *J. Drain. Irrig. Mach. Eng.* **25**(5) 24-28
[4] Tanweer S D and Gahlot V K 2010 Simulation of flow through a pump sump and its validation *J. IJRRAS* **4**(1) 7-17
[5] Kim C G, Choi Y D, Choi J W and Lee Y H 2012 A study on the effectiveness of an anti vortex device in the sump model by experiment and CFD *The Hydraulic Machinery and Systems 26th IAHR Symp (Beijing, China, 19-23 August, 2012)*
[6] Kang W T, Shin B R and Doh D H 2014 An effective shape of floor splitter for reducing sub-surface vortices in pump sump *J. Mech. Sci. Technol* **28**(1) 175-182
[7] Shabayek A S 2010 Improving approach flow hydraulics at pump intakes *IJCEE* **10** (6) 23-31
[8] Luo C, Qian J, Liu C, Chen F, Xu J and Zhou Q L 2015 Numerical simulation and test verification on diversion pier rectifying flow in forebay of pumping station for asymmertic combined sluice-pump station project *Trans. Chin. Soc. Agric. Eng.* **31** (7) 100-180
[9] GB/T 29531-2013 *Methods of Measuring and Evaluating Vibration of Pumps*
[10] He C L 2015 *Site Test Report of Yonghu Pumping Station Phase ⅡProject of Shenzhen (Tianjin: China Water Resources Beifang Investigation Design and Research Co. Ltd, Internal Report, in Chinese)*
[11] Wang F J 2004 *Computational Fluid Dynamic Analysis –CFD Principes and Applicatio*n (Beijing: Tsinghua University Press)
[12] Chen L, Liu C, Tang F P, Zhou J R and Yang H 2007 3D-numerical simulation and preformance predication of vertical axial flow pumping station *5th Joint ASME/JSME Fluids Engineering Conference (California, USA, July 30-August 2, 2007)*
[13] Lu L G, Cao Z G and Zhou J R 1997 The optimum hydraulic design of pump intakes *J. Hydraul. Eng.* **3** 16-25